In-Situ Metrology: the Path to Real-Time Advanced Process Control

Gary W. Rubloff

Professor, Materials Science and Engineering, Institute for Systems Research, and Electrical and Computer Engineering
University of Maryland

www.isr.umd.edu/gwrubloff, rubloff@isr.umd.edu
Synopsis

• Advanced process control (APC) has become pervasive
  – In-situ metrology is key to achieving real-time APC

• In-situ chemical sensors provide viable quantitative real-time metrology
  – Multiple sensors deliver <1% precision
  – Real-time end point control demonstrated
  – Course correction as well as fault detection
  – Application to CVD, PECVD, etch, spin-cast, …

• New opportunities
  – Uniformity control ➔ spatially programmable reactor design
  – Precursor delivery control ➔ solid & low $p_{vapor}$ sources
Advanced Process Control (APC)

- Course correction: Compensate for variations to maintain process targets
- Fault management: Identify and repair equipment problems
- Fault classification & response: Optimize management of faults
- Real-time control: End point and instantaneous
- Real-time fault detection: Known failure modes and signatures

- Advanced Process Control (APC)
- Sensor-driven
- Model-based

- Feedback & feedforward control
- Fault classification & response
- Real-time fault detection
- Run-to-run feedback control
- Run-to-run feedforward control
- Real-time control
- Real-time fault detection
- Run-to-run control

- Deposition
- Pattern generation
- Metrology
- Etching
APC Hierarchy

Factory Control System

Course correction
- Run-to-run course correction
- feedback
- feedforward

Fault management
- Tool maintenance
  - fault diagnosis
  - PM scheduling

Regulatory tool control
- equipment state

Tool Control System

In-line & other metrology
- Multi-step process control
- Multi-scale time response

In-situ, real-time process sensors
- Unit process control
- Real-time response

Real-time equipment sensors
- Equipment component control
- Real-time response

quantitative metrology
in-situ, real-time

supervisory

regulatory
In-Situ Sensors for Quantitative Process Metrology

**REQUIREMENTS**

- In-situ, real-time
- Quantitative precision (~1%)
  - *Required for course correction*

- Process state
- Wafer state
- Preferably multi-use
  - *Indicators of process & wafer state*
  - *Simultaneous application for fault detection*

- Rich information
  - *Chemically specific*
- Robust, integratable

**TECHNIQUES**

- Plasma optical emission spectroscopy (OES)
- Laser/optical interferometry
- Mass spectrometry
- Acoustic sensing
- Fourier transform infrared spectroscopy (FTIR)
- Plasma impedance
- Optical thermometry/pyrometry
- Ellipsometry
- Optical scatterometry
- ...

[Image of the page]
Mass Spectrometry for Real-Time APC

Ulvac multi-chamber “cluster” tool

PROCESS CHAMBER

Chemical vapor deposition chamber for tungsten metal

CHEMICAL SENSORS

Inficon Composer™ acoustic sensor

Inficon Transpector™ mass spec chemical sensor

Pressure transduction to low pressure
Real-Time Mass Spec in W CVD

- **W CVD by SiH₄ reduction of WF₆ in 0.5 torr thermal CVD**

- **Monitor process state as gas concentrations in reactor**

- **Product generation and reactant depletion reveal wafer state changes in real time**

\[
2 \text{WF}_6(g) + 3 \text{SiH}_4(g) \rightarrow 2 \text{W}(s) + 3 \text{SiF}_4(g) + 6 \text{H}_2(g)
\]

\[
\text{WF}_6(g) + \text{SiH}_4(g) \rightarrow \text{W}(s) + 2 \text{SiHF}_3(g) + 3 \text{H}_2(g)
\]
Real-Time Thickness Metrology

- Reasonable Conversion Rate of WF\textsubscript{6} reactant (~20%)

- Metrology established from weight vs. integrated mass spec signal
  - Linear regression  \( \rightarrow \) standard deviation 1.09%

- Viable for manufacturing process control
Real-Time Thickness Control

- Open-loop wafer-to-wafer thickness variation ~ 10%
- Real-time end-point control to ~ 3%
- Real-time course correction to compensate for BOTH:
  - Random short-term variability
  - Systematic longer-term drift
Mass Spec Thickness Metrology

**H₂ reduction of WF₆**

\[ WF₆(g) + 3 \, H₂(g) \rightarrow W(s) + 6 \, HF(g) \]

Fixed process condition: 10 torr, 500°C, 640 sec

**Run-to-run thickness drift**
- Average 1.18%
- Extreme 3.99%

**Mass spec thickness metrology**
- Average uncertainty 0.56%
- Standard deviation 0.72%

---

A. JAMES CLARK
SCHOOL OF ENGINEERING

2003 Int'l. Conf. Characterization & Metrology for ULSI Technology
G. W. Rubloff © 2003
Mass Spec Thickness Metrology: Intentional Temperature Drift

- Introduce significant temperature drift to test robustness of metrology

- Substantial change in thickness (4X)
  - Much larger than expected in manufacturing
Mass Spec Thickness Metrology: Intentional Temperature Drift

Moderate non-linearity over broad temperature range
Deposition on showerhead, adsorption on chamber walls, …

Metrology precision ~ 0.5% near local process setpoint
Mass Spec Thickness Metrology: Intentional Process Time Drift

- Introduce significant process time drift to test robustness of metrology
  - Substantial change in thickness (4X)
    - Much larger than expected in manufacturing
- Linear regression fit
  - Average uncertainty 1.19%
  - Standard deviation 1.59%
- Quadratic regression fit
  - Average uncertainty 0.48%
  - Standard deviation 0.57%

\[ \text{H}_2 \text{ reduction of WF}_6 \]
\[ \text{WF}_6(g) + 3 \text{H}_2(g) \rightarrow W(s) + 6 \text{HF}(g) \]
10 torr, 390°C
Seed (Nucleation) Layer Growth

Initial nucleation dominated by WF₆ - Si reaction in presence of H₂/WF₆ CVD reactants

Forms ~30 nm thick W film

Reduced HF production during nucleation stage

Possible fault detection application (assure oxide-free contacts)

Sensitivity for ultrathin barrier layer CVD processes
Acoustic Sensing for Real-Time APC

- Acoustic wave propagation and resonance
  \[ P > 50 \text{ torr} \]

- Resonant frequency depends on average molecular weight, specific heat, and temperature of gas mixture
  \[ C = \text{speed of sound} \]
  \[ F = \frac{C}{2L} \quad \text{with} \quad C = \sqrt{\frac{\gamma_{\text{avg}} RT}{M_{\text{avg}}}} \]

\[ \text{Pressure transduction to higher pressure} \]
Acoustic Sensor Thickness Metrology

**Run-to-run thickness drift**
Average 4% over 10 runs

**Acoustic sensor thickness metrology**
0.5% average uncertainty from linear regression fit

$\text{H}_2 \text{ reduction of WF}_6$

$$\text{WF}_6(g) + 3 \text{H}_2(g) \rightarrow \text{W}(s) + 6 \text{HF}(g)$$

Fixed process condition: 10 torr, 490°C, 640 sec

---

**Graph**
- Linear Fit of Data
- Frequency integrated signal (Hz.s)
- Estimated film thickness (Å)
- +/- 1% weight error

**Table**
- W film weight (g)
- Frequency integrated signal (Hz.s)
- Estimated film thickness (Å)

---

*Wafer 203 to 212*
*Linear Fit of Data2_B*
*Average 4% over 10 runs*
*0.5% average uncertainty from linear regression fit*
FTIR Sensing for Real-Time APC

- Implementation like acoustic sensor
  \[ P > 50 \text{ torr} \]
- Sense molecular vibrations (infrared) for product generation, reactant depletion
- \( WF_6 \) product depletion \( \Rightarrow \) thickness metrology precision \( \sim 0.5\% \)

H\(_2\) reduction of WF\(_6\)

\[ WF_6(g) + 3 H_2(g) \rightarrow W(s) + 6 HF(g) \]

Intentional temperature drift: 10 torr, 390-450°C

![Graph showing peak absorbance at 712.5 cm\(^{-1}\) and integrated WF\(_6\) signal as functions of time and mass of deposited tungsten.](image)

![Graph showing relationship between absorbance at 712.5 cm\(^{-1}\) and mass of deposited tungsten.](image)

\( R = 0.99672 \)
Sensor Integration

Sensor integration involves real-time control, equipment state, and sensor control. The diagram shows the interactions between the process and wafer state metrology, equipment state, real-time control, and dynamic system simulation.

- **Real-time control** involves sensor control and dynamic system simulation.
- **Equipment state** is managed by tool control and sensor control.
- **Process & wafer state metrology** is integrated with real-time control.

Key components include:
- **W CVD Reactor**
- **Central wafer handler**
- **Load lock**
- **Ultra ERA-1000 W CVD cluster tool**
- **Pump system**
- **LabView**
- **Brooks**
- **VisSim**

The integration of these components allows for effective monitoring and control of the manufacturing process.
Ready for Technology Transfer

• **In-situ sensors deliver metrology for real-time APC**
  – *Quantitative precision for real-time course correction*
  – *Dual-use sensors to drive both course correction and fault management (e.g., mass spec)*

• **Research underpinnings in place**
  – *Multiple sensors with metrology at 1% or better*
  – *Real-time end point control demonstrated*
  – *Sensor-tool integration*

• **Ready for implementation in manufacturing environment**
  – *Compatible with existing-installed real-time sensors for fault detection*
  – *UMD anxious to assist, collaborate, …*
  – **Prediction: further improvement in metrology precision**
    • High throughput enhances sensor & tool conditioning
Across-Wafer Uniformity

• Key manufacturing metric for yield

• Limited in-situ sensor capability to date
  – Full-wafer interferometry – wafer state
  – Spatially resolved optical (OES) – process state

• No mechanism for real-time uniformity adjustment

• Process optimization involves tradeoff between material quality metrics and uniformity

Choose compromise as process design to balance uniformity and material quality for fixed reactor configuration

Material quality

Uniformity

Recipe 1

Recipe 2

Recipe 3
Spatially Programmable CVD Uniformity through a **Smart Showerhead**

**Sensors** - integrated into the showerhead
- Spatially resolved, multizone wafer and process state measurements

**Actuators** - multizone, gas inlet
- Gas flow rates and compositions controlled within each showerhead segment

**Supplementary pumping through the showerhead**
- Reduced inter-segment gas mixing, precise composition control, gas sampling for chemical sensing

**Simulation and reduced-order models**
- Support for process equipment design and control

---

**Programmable Uniformity for Enhanced Manufacturing**
Programmable Nonuniformity
for Rapid Materials & Process Development

One-wafer DOE \(\rightarrow\) process optimization

Combinatorial CVD \(\rightarrow\) new materials discovery and development
Precursor Delivery Challenges

- Solid & low vapor pressure sources increasingly critical for new materials
- Precursor delivery control remains problematic
  - Changing morphology with time and usage
  - Adsorption on walls
  - Complex chemical precursors
- Options limited for both chemical precursor and delivery system design

Example: Cp₂Mg temperature decrease 40°C to 32°C reduces vapor pressure & composition 2X
  Simulates “aging” effects
Real-Time Precursor Delivery Control

- Acoustic sensor for composition metrology
- Source and dilution gas flow control

Source temperature varied from 40 to 32°C
$\Sigma (H_2 \text{ flows}) = 150 \text{ sccm}, P = 300 \text{ torr}$
$Cp_2Mg$ target = 0.01 mol%

$Cp_2Mg$ composition controlled to 1% of target (0.0001 mol %)
Conclusions

• **In-situ metrology is key to achieving real-time APC**
  – *Benefits in rapid feedback at unit process (tool) level*
  – *Implementation within hierarchical control framework*

• **In-situ chemical sensors provide quantitative real-time metrology**
  – *Multiple sensors with <1% precision*
  – *Real-time end point control demonstrated*
  – *Course correction synergistic with fault detection*
  – *Broad applications - CVD, PECVD, etch, spin-cast, …*

• **Ready for tech transfer, evaluation in manufacturing environment**

• **New opportunities**
  – *Uniformity control*
  – *Precursor delivery control*
Acknowledgements

• **Research group**

• **NIST**
  – J. Whetstone, A. Lee, C. Tilford

• **Inficon**
  – R. Ellefson, L. Frees, C. Gogol, A. Wajid, J. Kushneir

• **Other colleagues**
  – Metrology TWG, AEC/APC, AVS MSTG

• **Support**